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THESIS

HOLOGRAPHIC PARTICLE SIZING
IN
SOLID FUEL RAMJETS

by

Robert P. Paty

September 1988

Thesis Advisor: David W. Netzer

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An investigation was conducted to determine the suitability of a holographic technique as a diagnostic tool for metallized fuel combustion in a two-dimensional solid fuel ramjet. The highly metallized fuels were burned under conditions similar to actual flight conditions.If found suitable, the objective was to produce a three-dimensional image of a volume in the boundary layer above the fuel surface, and to determine the particle size distribution in that volume. This distribution could be used to validate current models which must assume particle size, and could lead to better estimates of fuel regression rates and combustion efficiencies. Once the conditions for sustained combustion were determined, the technique was successfully demonstrated, even in the presence of large amounts of smoke. Holograms were obtained at two different chamber pressures for each of the fuels. However, current resolution limits of the technique are not sufficient to reveal the vast majority of the particles in the combustor.

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Holographic Particle Sizing
in
Solid Fuel Ramjets

by

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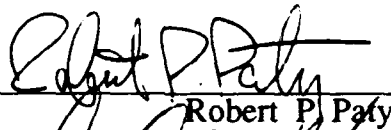B.S., Texas A&M University, 1979

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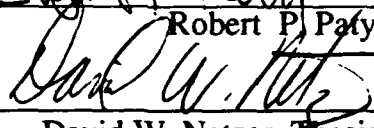
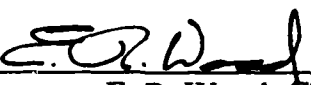# MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

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ABSTRACT

An investigation was conducted to determine the suitability of a holographic technique as a diagnostic tool for metallized fuel combustion in a two-dimensional solid fuel ramjet. The highly metallized fuels were burned under conditions similar to actual flight conditions. If found suitable, the objective was to produce a three-dimensional image of a volume in the boundary layer above the fuel surface, and to determine the particle size distribution in that volume. This distribution could be used to validate current models which must assume particle size, and could lead to better estimates of fuel regression rates and combustion efficiencies. Once the conditions for sustained combustion of the fuels were determined, the technique was successfully demonstrated, even in the presence of large amounts of smoke. Holograms were obtained at two different chamber pressures for each of the fuels. However, current resolution limits of the technique are not sufficient to reveal the vast majority of the particles in the combustor.

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I. INTRODUCTION

The ideological advantages of the integral rocket ramjet as an option for near term tactical missile applications are well documented. Ramjet sustainers buy the firing platform survivability in the form of increased stand-off distance. Lethality is enhanced since the missile can be powered to intercept. Rockets often cannot meet the energy demands placed on the high specific impulse of the ramjet. Liquid fuel versions generally exhibit the highest combustion efficiencies at a variety of flight conditions and longer flight durations, but the self-throttling feature of solid fuel ramjets makes them competitive if operating envelopes and mission requirements are not excessive [Ref. 1:p. 4].

Non-metallized fuels for the solid fuel ramjet have been well characterized in extensive experimentation and modeling. The combustion process for these fuels is well understood. To be competitive with other forms of propulsion, though, fuels with higher energy content and density are required. Metallized fuels show promise in this regard, but have proven more difficult to characterize. The most important characteristics of a solid fuel combustor are its flameholding limits, the regression rate of the fuel, and the combustion efficiency [Ref. 1:p. 12]. The most important fuel characteristics are energy content[1], density, storability, and good combustibility [Ref. 2:p. 2]. Unfortunately, many metallized fuel candidates with very high energy content have tended to have poor combustion efficiencies.

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[1]Energy content may be characterized as enthalpy of combustion per unit mass or per unit volume (energy density) of fuel. If fuel space is severely restricted, energy density may become the driving fuel selection factor.

Particles tend to agglomerate at the surface of the fuel as the surrounding binder is vaporized. Once the particles of various sizes are ejected into the combustor, there are several problems inherent in metal particle combustion . If combustion is poor, two-phase flow losses alone can become significant.

Given these combustion problems and the difficulty in characterizing metallized fuels, knowing the particle size distribution in the combustor could lead to improvements in the estimates for regression rate, two-phase flow losses, and combustion efficiency. It would also provide data for validation of current combustion models which must assume the particle sizes. Fuel additives and alternate combustion geometries (e.g., recirculation zone shape and bypass configuration) also affect the combustion process; generally in an unpredictable manner. Having particle size data for these alternate effects would greatly aid the motor design process. The ramjet combustor is at best a severe environment for obtaining the needed particle data, particularly for optical measurements. Karadimitris [Ref. 3] took high speed motion pictures of metallized fuel combustion in a recirculation zone and in the boundary layer region, utilizing a windowed two-dimensional motor. The problems associated with photography are resolution (approximately 20 microns with any reasonable depth of field) and the fact that the flame around each particle obscures its size. In addition, the limited depth of field restricts the observations to the region near the wall where window purge can affect the combustion process. The advantage of the motion pictures is that particle behavior over time can be recorded. Easterling [Ref. 4] proposed to use holography to remove the flame obscuration, improve the resolution, and record the entire combustor volume within the field of view of the windows. The disadvantage is that only one instant of time is recorded. This investigation was

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directed at overcoming the technical difficulties in applying the holographic technique to a two-dimensional solid fuel ramjet. The primary objective was to determine if holography is indeed an appropriate diagnostic tool in this application. If so, it could be used to determine particle size distributions in metallized fuel combustion for several different fuels at various air mass flux and combustor pressure conditions. The main questions to be answered were: (1) are obscurations low enough to permit good quality holograms to be obtained, and (2) what are the resolution limits if diffuse scene beams (in the presence of the resulting speckle) are required to overcome the thermal gradients surrounding the burning metallic particles.

Light scattering techniques can also be used to measure particle sizes. However, the particles must generally be nearly spherical for this diagnostic technique to be used. Holography can be used to determine the shapes of the metallic agglomerates within the solid fuel ramjet combustor.

II. BACKGROUND

A. RAMJET OPERATING PRINCIPLE

The basic ramjet is the simplest of airbreathing engines, having no moving parts. The diffuser acts as compressor section, slowing inlet air and increasing static pressure. Solid fuel ramjets have no need for the fuel management and injection systems of their liquid fuel counterparts. The combustor section consists of some type of flameholder in the head end such as a rearward facing step or a side dump inlet, the fuel grain in the main combustor section, and possibly an aft mixing chamber with or without bypass air to increase residence time and combustion efficiency. An exhaust nozzle completes the engine. Figure 2.1 outlines the performance range of ramjets.

One disadvantage of ramjets is the lack of zero airspeed start capability. They must be boosted to a minimum velocity of approximately Mach 1.5 to begin operation. Figure 2.2 shows a possible integral rocket ramjet configuration where the rocket booster grain and the ramjet sustainer grain share the same combustor. This eliminates the need for "strap-on" boosters. At takeover velocity, the ramjet inlet diffuser provides a high temperature and pressure subsonic flow. After ignition, the energy release from combustion is sufficient for the engine to become self-sustaining, and the nozzle provides the conversion to kinetic energy necessary for thrust production.

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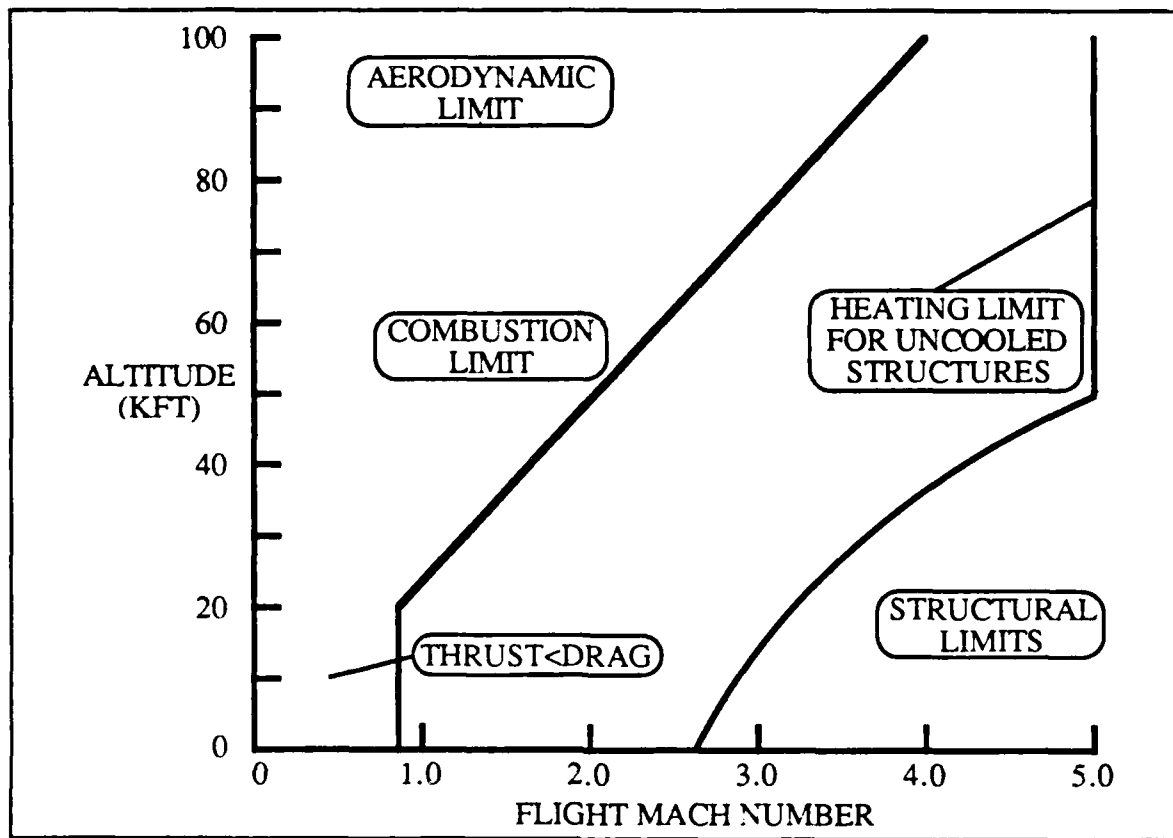
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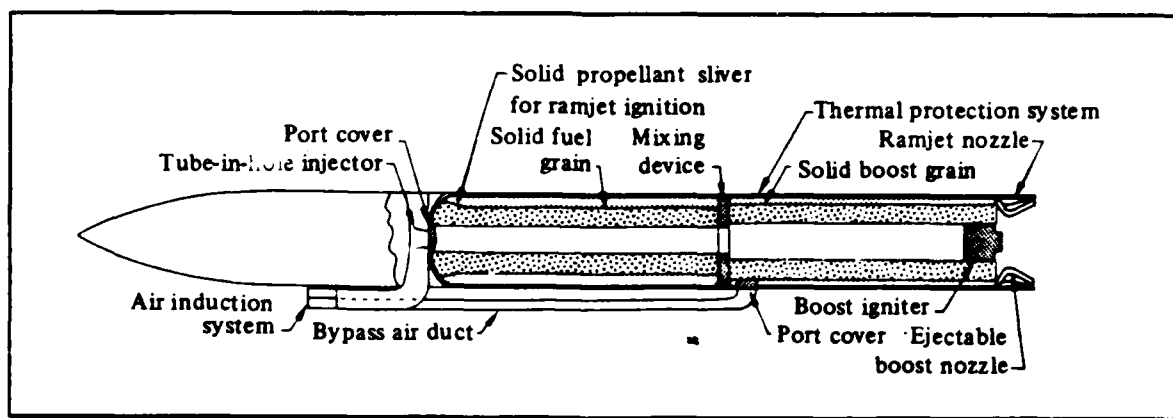
Figure 2.2. Bypass-type, Solid-fueled, Integral Rocket Ramjet
[Ref. 5:p. 40]

B. COMBUSTION CHARACTERISTICS OF SOLID FUEL RAMJETS

A representative diagram of the flow in a two-dimensional solid fuel ramjet is shown in Figure 2.3. Operationally, of course, the typical motor is axisymmetric with a cylindrical grain cast in the missile case. The operational simplicity of the ramjet is belied by the difficulty in selecting a configuration and fuel grain for a specific application. Myers [Ref. 7:p. 1] cites the following special problems associated with solid fuel ramjets:

- Selection of a fuel type
- Flameholding requirements that limit maximum fuel loading
- Fuel regression rate as a function of flight speed and altitude
- Diffusion controlled combustion process that requires special mixing section
- Inlet/combustor matching
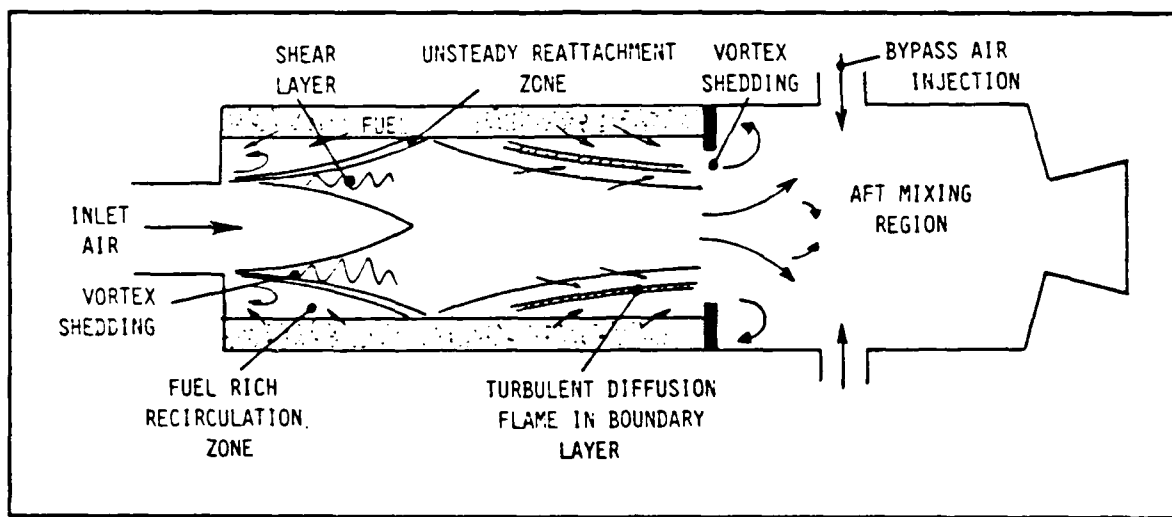
Figure 2.3. Basic Solid Fuel Ramjet Geometric Features and Flow Characteristics [Ref. 6:p. 159]

United Technologies Chemical Systems [Ref. 1:p. 12] addresses solid fuel ramjet combustion as follows:

The principles underlying SFRJ combustion are: (1) developing a stable, high temperature recirculation zone to ensure flameholding, (2) providing a combustor length to diameter ratio adequate to permit full flame spreading within the combustor, and (3) achieving satisfactory mixing of vaporized fuel and air to ensure complete reaction before the combustion gases exit through the exhaust nozzle.

Each of these principles and problems are addressed as they relate to each section of the combustor.

1. Head-End

The head-end encompasses the air inlet and the recirculation zone geometry, which in this investigation was a rearward facing step (see Figure 2.3). This causes flow separation and sudden expansion, resulting in a hot, fuel rich mixture in the recirculation zone. There is a minimum step height necessary for sustained combustion. The critical parameter is the ratio of the fuel port area to the area of the air inlet, and its required value is dependent on the fuel composition. Another critical parameter is the ratio of the fuel port area to the nozzle throat area. This determines the port velocity, which if excessive will cause blowoff. Finally, an increase in inlet air stagnation temperature enhances flame stabilization. The effects of these three parameters are illustrated in Figure 2.4
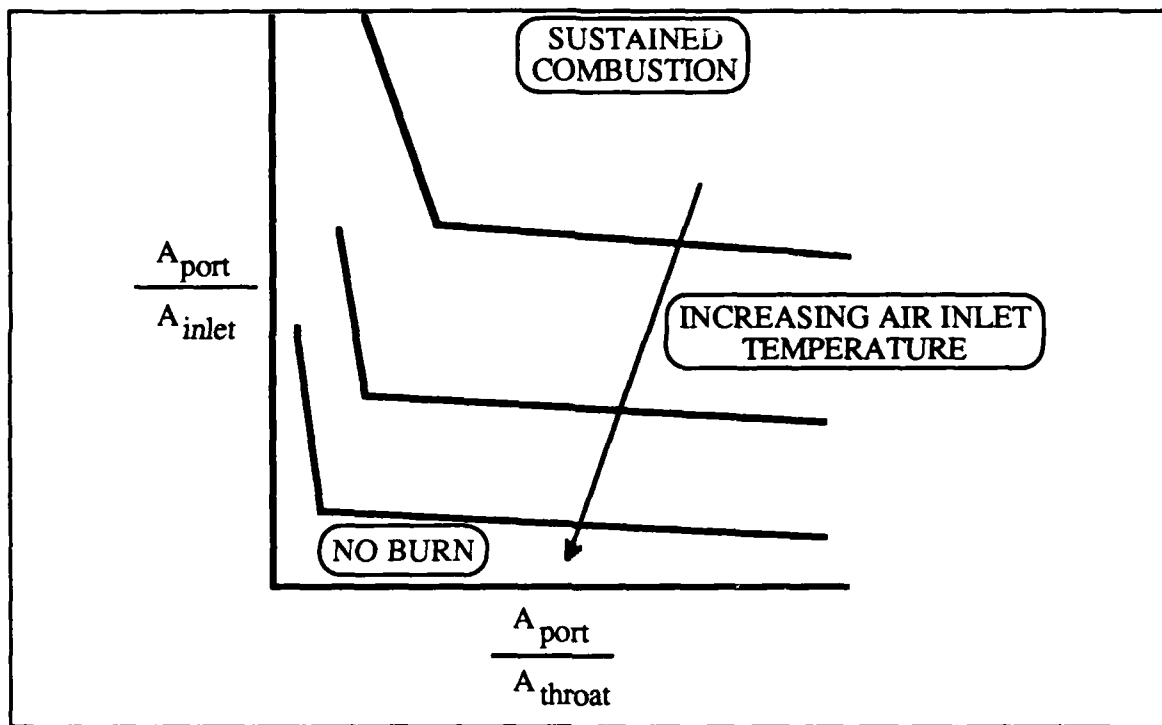
Figure 2.4. Typical Solid Fuel Ramjet Flammability Limits
[Ref.6:p. 160]

2. Main Combustor

The main combustor in a solid fuel ramjet begins with the recirculation zone just aft of the inlet. The fuel grain lines the combustor. In the case of an integral rocket ramjet, the fuel grain is further lined by the booster propellant grain (see Figure 2.2). The flow, separated by the inlet step, establishes an unsteady reattachment point downstream of the recirculation zone. The centerline of the combustor remains oxygen rich, and the boundary layer above the fuel grain becomes fuel rich as radiative and convective heat transfer vaporize the fuel surface. A self-sustained diffusion flame results between the two regions. [Ref. 6:p. 159] The peculiarities of metallized fuel combustion will be addressed later. In a two-dimensional motor, the diffusion flame may be visualized as a plane above the fuel surface. This lends itself well to holographic techniques since one can then

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"see" the combustion process along the motor centerline, relatively free of any effects from the side walls or viewing windows.

The regression rate of the fuel depends on the convective and radiative heat transfer from the diffusion flame to the fuel surface. Experimentally, the former has been found to be primarily determined by air mass flux and inlet air temperature. It is also influenced by port diameter, presumably because the distance from the flame to the fuel surface increases with increasing port size [Ref. 8:p. 303]. The radiative heat transfer is determined by combustion pressure, combustion zone thickness, and flame temperture [Ref. 1:p. 16]. The dependence of the regression rate on these various parameters can vary significantly from one fuel to another, but once characterized, design choices are simplified. It must also be remembered that changing flight conditions will influence regression rate, hence the self-throttling character of the solid fuel ramjet. Further, characteristics will change throughout burning as the fuel regresses, increasing the port diameter and burning surface area. Regression rate may be increased by the addition of swirl generators upstream of the combustion inlet. Some regression rate control may also be possible with a variable bypass configuration where a portion of the inlet air passes through the combustor, and the remaining air enters an aft mixing section. Since not all of the air passes through the combustor, the port area may be smaller without port Mach number becoming excessive [Ref. 5:p. 40]. This has the additional advantages of increasing available fuel volume in the combustor and often increasing combustion efficiency. [Ref. 6:p. 159]

3. Aft Mixing Chamber

Even for non-metallized fuels, complete combustion is not assured. Some vaporized fuel may not reach the diffusion flame, and hence does not burn. Some

type of mixing device is often added downstream of the combustor to enhance mixing of the air-rich and fuel-rich gases. Combustion efficiency can be significantly improved. The mixing device may take the form of a diaphragm or vanes, for example. In this investigation it was simply an extension of the combustor, without fuel, to increase the residence time of the gases in the motor. The addition of bypass air into this section may further improve efficiency. [Ref. 6:p. 160]

4. Exit Nozzle

The exit nozzle produces thrust by converting some of the enthalpy of combustion to kinetic energy. From a performance standpoint, a continuously variable nozzle which optimizes performance at any flight condition would appear ideal. However, complexity, weight, and cost are most often prohibitive. The usual nozzle has fixed throat area. In an integral rocket ramjet the booster operates at pressures an order of magnitude higher than the ramjet. This requires the use of a smaller exhaust nozzle. One solution is an ejectable booster nozzle inside the ramjet nozzle. There are other options, including the concept of a nozzleless booster. In this case the cost and complexity of the nozzle are avoided altogether, and the space vacated by the nozzle may be filled with additional propellant to make up some of the lost specific impulse. [Ref. 5:pp. 44-45]

C. METALLIZED FUELS

1. High Energetic Performance Fuels

As mentioned earlier, for solid fuel ramjets to be competitive with other forms of propulsion, alternatives to the standard hydrocarbon fuels must often be considered. One parameter used to characterize airbreathing propulsion systems is the specific impulse (I_{sp}). For comparison of combustors, the static specific

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impulse, in which the inlet air has no axial momentum, is convenient. Gany and Netzer [Ref. 6:p. 158] point out that for ramjets with similar static thrust, the static specific impulse is linearly proportional to the heat release per unit mass of fuel, also called the enthalpy of combustion. They conclude that ramjet performance in terms of the static specific impulse may be characterized by the enthalpy of combustion per unit mass of fuel($-\Delta H^{\circ}_R$). The energy density, or enthalpy of combustion per unit volume of fuel ($-\rho\Delta H^{\circ}_R$) may become a primary fuel selection criterion in situations where the fuel volume is restricted.

Figure 2.5 shows the heat of combustion (in oxygen) per unit mass and per unit volume for certain elements versus atomic number. Values for a representative hydrocarbon are included for comparison. In the selection of a suitable ramjet fuel, there are many attractive candidates, but consideration must be given to ignition and combustion characteristics, toxicity, cost, handling, and other concerns. For example, elemental hydrogen has the highest enthalpy of combustion per unit mass but occurs naturally as a diatomic gas. Therefore, hydrogen may only be used in a solid fuel ramjet as it occurs in solid compounds such as some metal hydrides, which may have merit as fuels. A second example, boron is rather expensive and has ignitability and combustibility problems. However, boron carbide (B_4C) is readily available, relatively inexpensive, and has just slightly lower performance. Gany and Netzer [Ref. 6] provide energetic performance criteria for a large variety of fuel candidates as well as more subjective criteria for the top performers. Factors such as ignitability, combustion efficiency, and particular mission profiles are not included in their discussion, but obviously must be considered in the design process.

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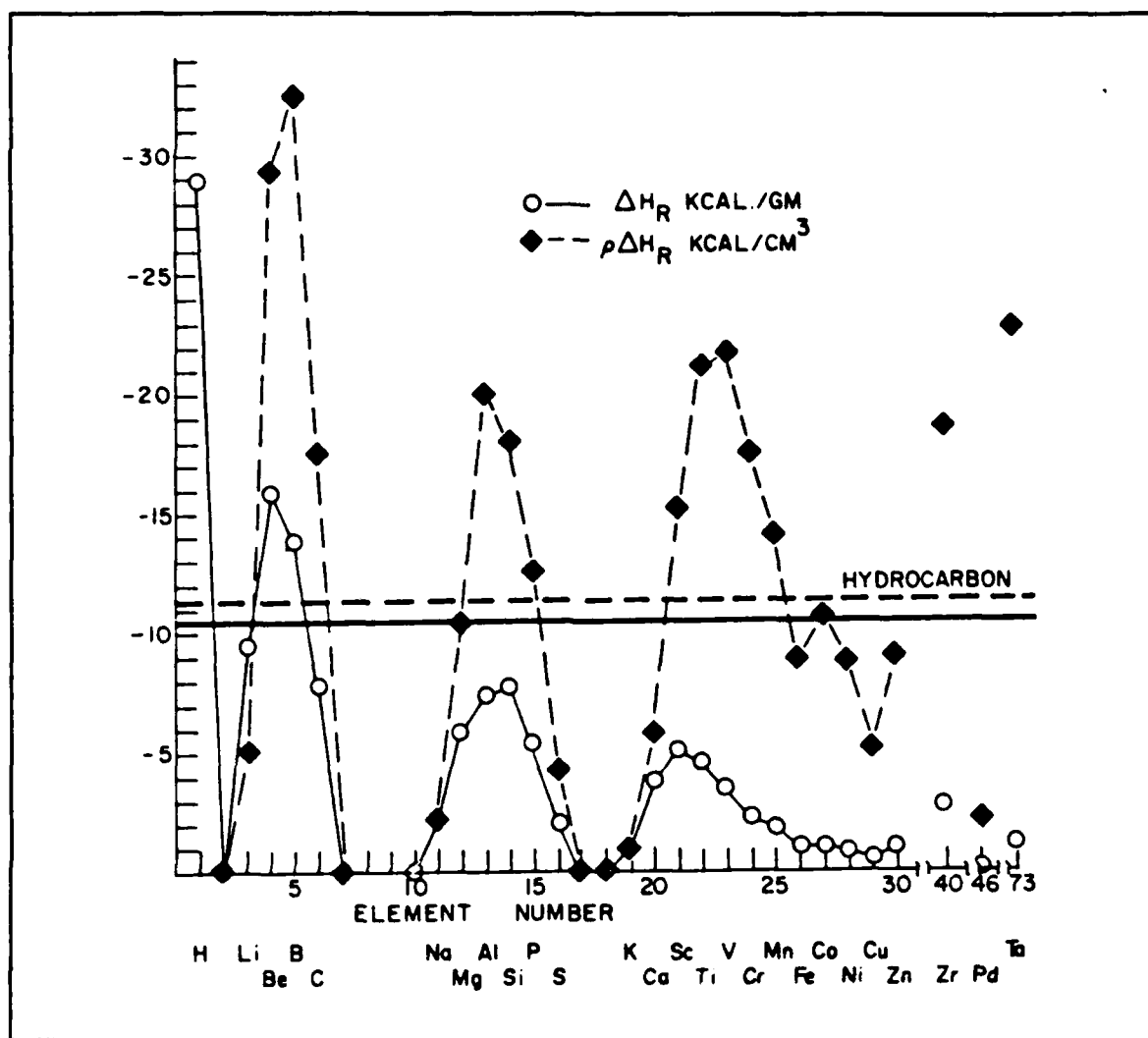
Figure 2.5. Heat of Combustion of Elements Per Unit Mass and Per
Unit Volume [Ref. 6:p. 161]

2. Combustion Characteristics of Metallized Fuels

The great potential of highly loaded metallized fuels has proven difficult to
realize. In those instances which produce acceptable combustion efficiencies, those
efficiencies are very condition sensitive. Because of very complex combustion
processes with metallized fuels, characterization is elusive and controversial.
Lessons learned from one formulation often do not translate well to others, making
modeling difficult. Much of this difficulty stems from a lack of information on the

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phenomena of metal particle combustion and how those particles enter the combustion area.

Powdered metals (typical particle size of 1 to 50 microns) are usually cast in a hydrocarbon matrix. Metal loading may be as high as 70%. The flow characteristics in the combustor are similar to those in a non-metallized fuel combustor. The particles may tend to agglomerate on the fuel surface as the surrounding matrix is vaporized. Since most of the heat release comes from metal particle combustion, the diffusion flame is probably less intense. It is still assumed that there will be almost no oxygen just above the surface, and therefore the particles must be ejected into the central port area in order to ignite and burn. Gany and Netzer [Ref. 9] noted hot spots of combustion near irregularities on the fuel surface using high speed motion pictures, presumably because the irregularities caused local mixing, allowing oxygen to reach the surface. Normally, however, the particles are heated on the surface and ejected, probably by pressure forces from the escaping vaporized matrix. The metal, if it reaches an area containing oxygen, will immediately be coated with an oxide layer which inhibits reaction rates. If initial temperatures are high enough, this layer will vaporize quickly, allowing ignition of the metal. If temperatures are too low, or the agglomerate too large, the oxide layer may not vaporize quickly enough, if at all. This results in incomplete combustion and two-phase flow losses. [Ref. 9:pp. 423-425]

Boron provides a good example of the complexity of metal particle combustion, and interest is keen due to boron's exceptional enthalpy of combustion. Many details are poorly understood, but the following description is widely supported. As stated above, the relatively low temperature particles enter the

combustor port with a solid oxide coating. Heat transfer from the surrounding gases causes the temperature to rise, and the oxide melts at about 720K. Boron and/or oxygen (a point of contention) diffuse across the oxide layer and reaction rates increase with temperature. The particle ignites and becomes luminous as reaction rates drastically increase. However, the reaction seems to slow rapidly as the oxide layer thickens and diffusion slows. If the temperature increases further, the oxide layer evaporates more readily and thins. At about 1900K, the evaporation rate is sufficient to remove the layer. Relatively rapid combustion of the remaining boron ensues. Again, parts of this process are poorly understood, and this is but one metal. Different metals and compounds, as well as their oxides, behave differently, and to varying degrees, unpredictably. [Ref. 10:pp. 1-3]

Further conditions are necessary for efficient combustion. In their theoretical investigation on the behavior of individual boron particles in the flowfield of a solid fuel ramjet combustor, Natan and Gany [Ref. 11:p. 5] note that boron particles are ejected basically in all directions, even upstream. They report a well defined "particle ignition zone" with respect to the particle's ejection location. The particle trajectory, a function of ejection angle and velocity, must pass through this zone for ignition to occur. Further, ignition doesn't guarantee combustion. A limited range of ejection velocities will enable both to occur, and larger particles have a smaller range. Ignition requires high temperatures, and efficient combustion requires an oxygen rich environment which is usually of relatively low temperature. Their calculations show that preheating particles upon ejection can significantly decrease burning time and distance for complete combustion. Additives to decrease agglomeration, and small amounts of oxidizer added to fuels are being investigated.

Any information regarding particle history in the combustor can only add to the understanding of these processes. High speed motion pictures show only the flame and not the particle. They are limited to the area adjacent to the viewing window where the flow may not be representative, and resolution is usually insufficient. Holography has the potential to record a representative volume with improved resolution to allow study of the particle size distibution.

D. HOLOGRAPHY

Conventional photography, including motion pictures, depends only on light intensity, and cannot record phase information. A hologram, however, by using a reference beam, can record intensity and phase information, allowing production of a three-dimensional image. A coherent laser beam is split into a scene beam which illuminates the object of interest, and a reference beam which is undisturbed. If the beams travel approximately the same distance to a point of coincidence, an interference pattern results from phase differences. This pattern, as well as intensity information, may be recorded on a photographic plate, forming a hologram. [Ref. 12]

The requirement for nearly equal path lengths results in minimal temporal coherence requirements. Spatial alignment of the beams at the point of coincidence is paramount. Four factors which affect the resolution of a hologram are: (1) the ratio of the beam intensities, (2) light intensity versus exposure time, (3) spatial alignment, and (4) vibration. Reconstruction of the hologram is achieved by illuminating it with laser light of the same wavelength as the original (the closer the wavelength to the original, the better the resolution). The result is a three-dimensional image of the object of interest in space, in the same position as the

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actual object, relative to the photographic plate. Consequently, any plane of the image may be studied and/or recorded with conventional means.

III. DESCRIPTION OF APPARATUS

The primary components of the experimental apparatus included a two-dimensional solid fuel ramjet preceeded by a vitiated air heater, ignition and purge systems, an automatic data acquisition and reduction system, remote control panels, a one joule, Q-switched pulsed ruby laser, and a holocamera.

A. TWO-DIMENSIONAL SOLID FUEL RAMJET

The two-dimensional ramjet used in this investigation consisted of the four sections discussed earlier: (1) head-end, (2) main combustor, (3) aft mixing section, and (4) exhaust nozzle. The simplicity of the layout is evident in Figure 3.1. The actual motor is shown with one side removed in Figure 3.2.
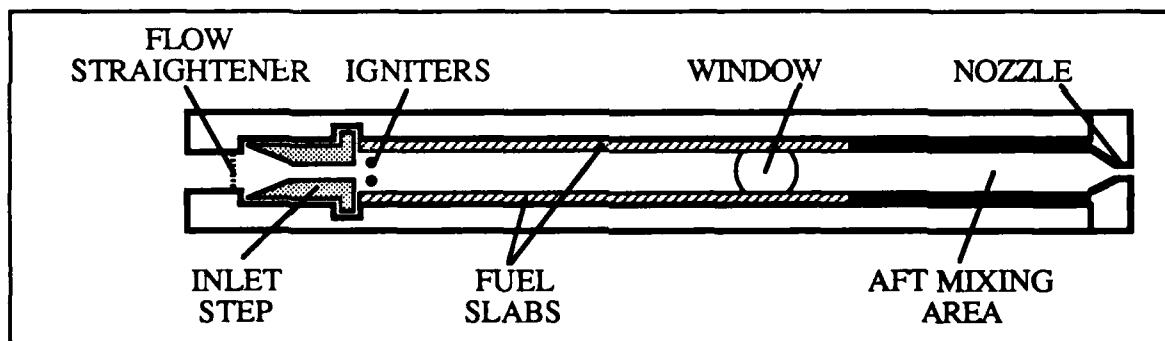
Figure 3.1. Diagram of the SFRJ Motor

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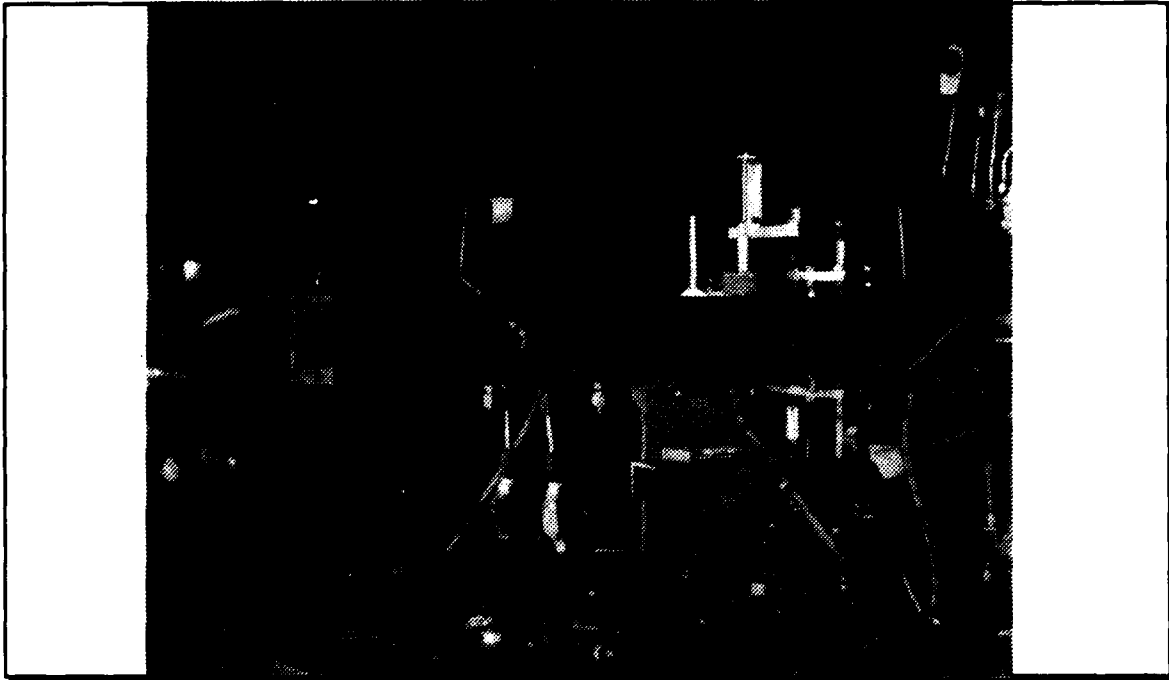
Figure 3.2. Solid Fuel Ramjet with Side Removed

Air from the vitiated air heater entered the head-end and first passed through a flow straightener followed by the variable inlet step. This arrangement allowed remotely controlled adjustment of step height and inlet port area. Flammability limits could thus be conveniently explored. A linear variable displacement transducer (LVDT) provided accurate step position data via a digital voltmeter. The step could also be adjusted during the run at a variable rate. To aid ignition, a small amount of ethylene (less than 0.7% of the air mass flow rate) was introduced into the recirculation zone through small ports in the aft faces of the inlet steps.

The main combustor was 2.5 inches wide, 16 inches long, and 1.5 inches high. The fuel slabs were nominally 0.25 inches thick and completely covered the top and bottom of the combustor, for a fuel port height of 1.0 inch. The slabs were held in place with silicon adhesive. One side of the motor had three viewing windows to allow high speed motion pictures to be taken in the recirculation zone, mid-

chamber, and just upstream of the aft mixing zone. For this investigation, the first two windows were fitted with block-off plates. The opposite side of the motor was fitted with a window opposite the third, so that the illuminating laser could pass through the combustor. The result was an illuminated cylindrical volume 0.375 inches in diameter and 2.5 inches long. The windows were 0.375 inch thick Plexiglas with 0.25 inch thick fused silica inserts. These windows were placed in assemblies like that illustrated in Figure 3.3 to supply purge air to prevent fowling and charring of the windows. Alignment was such that the illuminated volume was coincident with the bottom fuel slab surface to capture the boundary layer.
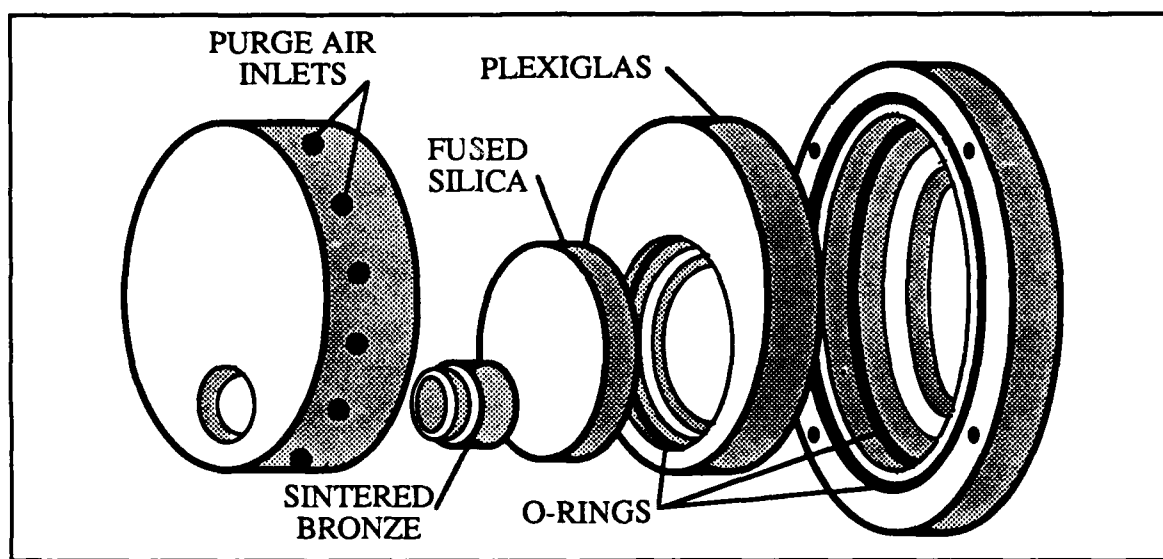
Figure 3.3. Window/Purge Assembly

The aft mixing section was 2.5 inches wide, 6 inches long, and 1.25 inches high. There is currently no provision for bypass air in this configuration. The nozzle was a machined graphite insert in the motor end cap. A variety of sizes were available to adjust combustor pressure. The assembled motor is shown in Figure 3.4.

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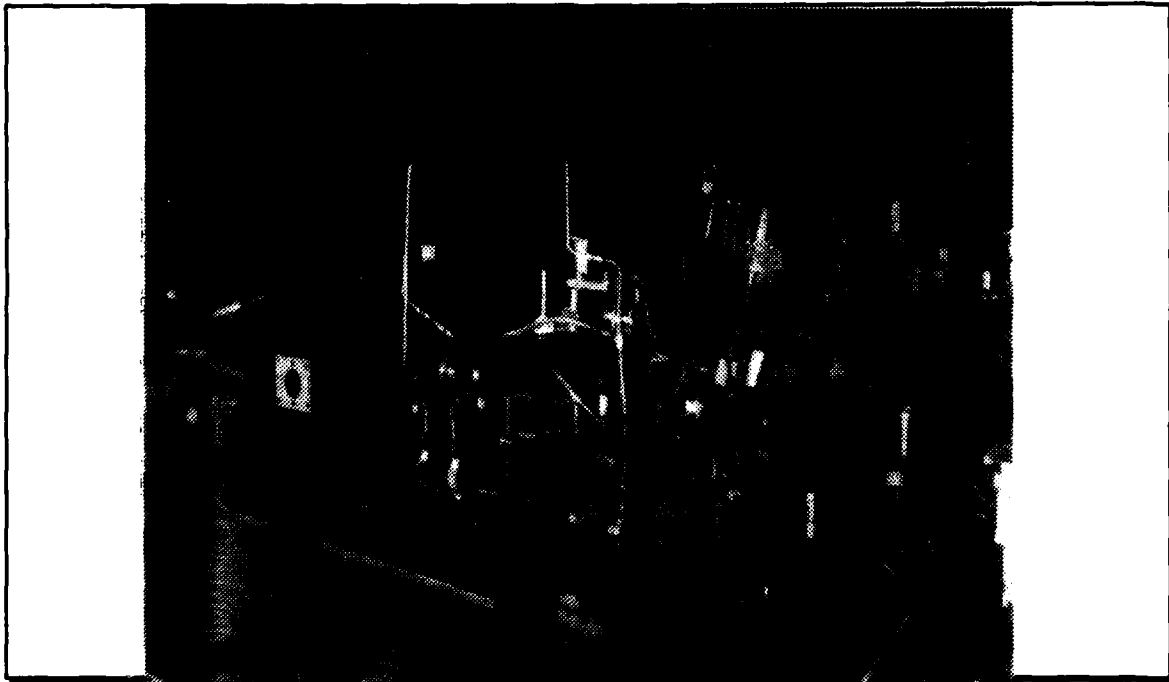
Figure 3.4. Solid Fuel Ramjet Assembled

B. VITIATED AIR HEATER

Actual ramjet inlet conditions were simulated using the vitiated air heater. A 3000 psi air system supplied the methane fired heater, and oxygen was supplied to replace that consumed in heater combustion. Gas mass flow rates were controlled using sonic chokes with sufficient pressure to assure that they remained choked. The system was capable of mass flow rates up to 2.5 lbm/sec at temperatures up to approximately 1500R. The heater was acoustically isolated from the motor with a sonically choked nozzle.

C. IGNITERS

Ignition of the solid fuel was achieved with two ethylene-oxygen torches visible in Figure 3.4. The torches were directed toward the inlet steps and across the fuel slabs (into the recirculation zone). As mentioned earlier, supplemental ethylene

was supplied through the inlet steps to aid ignition. Its mass flow rate was controlled in the same manner as the heater gases. Upon ignition, the motor self-sustained and the igniters and supplemental ethylene were secured.

D. PURGE SYSTEM

After the predetermined run period, inlet air was automatically dumped overboard and the heater secured. Simultaneously, nitrogen or argon was passed through the motor to extinguish combustion.

E. DATA ACQUISITION

Data acquisition, reduction, and system control were provided by a Hewlett-Packard 3054A system. Primary components were a HP-9836 computer, a 3497A data acquisition and control unit, amd two A/D integrating voltmeters (HP-3456A and HP-3437A).

F. REMOTE CONTROL

Three remote panels located in the control room provided manual and override control for the air heater, the ramjet, and the pulsed ruby laser. Controls on the first two included switches for all their associated gases and the respective igniters. Ramjet manual control also included a valve to dump inlet air overboard, and a valve to admit purge gas into the motor. The laser control panel provided switches for charging and discharging the capacitor bank, and for firing the laser. Two indicators displayed capacitor charge. Should the laser fail to fire and the capacitors subsequently fail to discharge, an emergency switch was available, further backed up by a manual shorting device.

G. RUBY LASER

The pulsed ruby laser holographic illuminator was a Kerr cell Q-switched oscillator with a 0.03 percent ruby rod. The rod output was expanded and collimated. All laser optics were located in one chest with a dark field autocollimator and a helium-neon laser for alignment. Cooling was provided by a separate cabinet containing coolant and a refrigeration system. Laser output was 1 joule in a 50 nanosecond pulse of 0.6943 micron wavelength light. [Ref. 13]

H. HOLOCAMERA

The lens-assisted reverse reference beam holocamera was designed and constructed specifically for this application [Ref. 4:p. 29], and was based on an existing AFRPL design [Ref. 14]. The removable lens-plate box and shutter electronics used in the AFRPL camera were retained. Figure 3.5 illustrates the basic operation of the camera. The collimated ruby laser pulse entered the camera and was deflected downward by a dielectric mirror to the splitter. 72% of the beam passed through the wedge beam splitter to become the scene beam. 15% of the beam was reflected off the upper surface of the splitter to become the reference beam. The remaining 13% was reflected off the lower surface of the splitter and not used. The scene beam was then turned 270 degrees by a pair of dielectric mirrors to make it parallel with the fuel slab surface. The two collimating lenses inverted the beam (required for spatial matching) through a small aperture. The scene beam entered the combustor after passing through a glass diffuser for a diffuse hologram, or through a neutral density filter for a collimated hologram. After passing through the motor windows and the scene volume, the beam entered the lens-plate box via two assisting lenses to enhance resolution, and an optical filter

to exclude any combustion flame light. The beam next passed through a Uniblitz shutter mounted on a removable plate, and struck the photograhic plate.
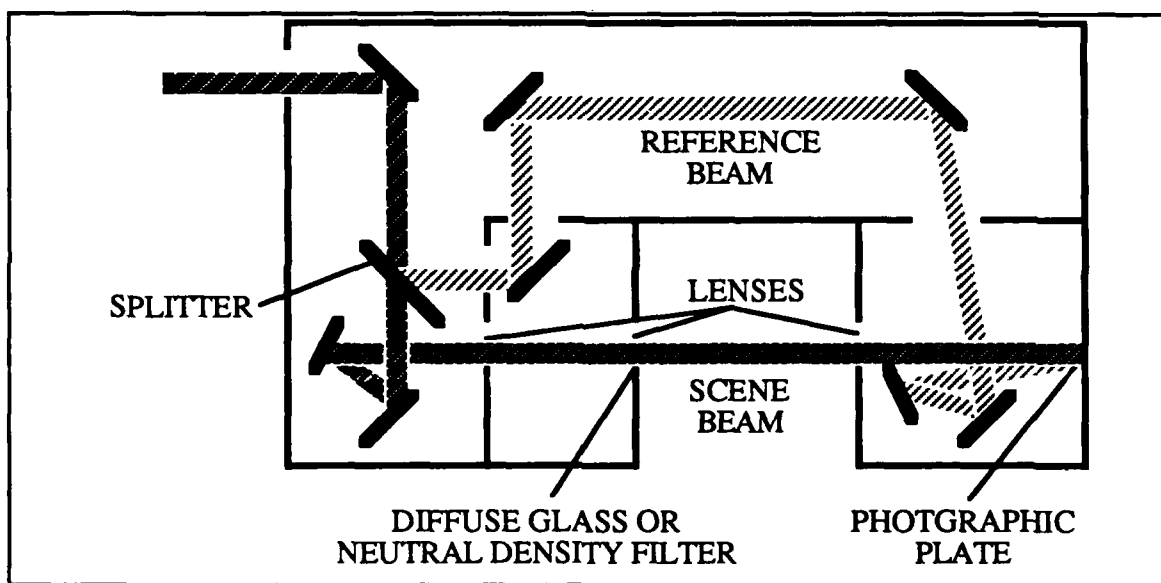
Figure 3.5. Basic Holocamera Operation

After reflecting off the splitter, the reference beam was turned first upward to avoid the motor, then parallel to the scene beam. It was next deflected downward into the lens-plate box where two more mirrors turned it to strike the photographic plate coincident with the scene beam, but at an angle of approximately 60 degrees.

Obviously, alignment of the two beams was critical, and additionally, the beam path lengths needed to be approximately equal. The first scene beam mirror was mounted on a translating base to adjust path length, and all the mirrors were mounted on rotating bases and three-axis optical mounts to permit independent elevation and azimuthal adjustments. In addition, the camera was mounted on the motor stand with three height adjustable legs. These legs were self-centering on three two-axis translators, providing accurate, repeatable alignment. The mounted camera is shown in Figure 3.6.
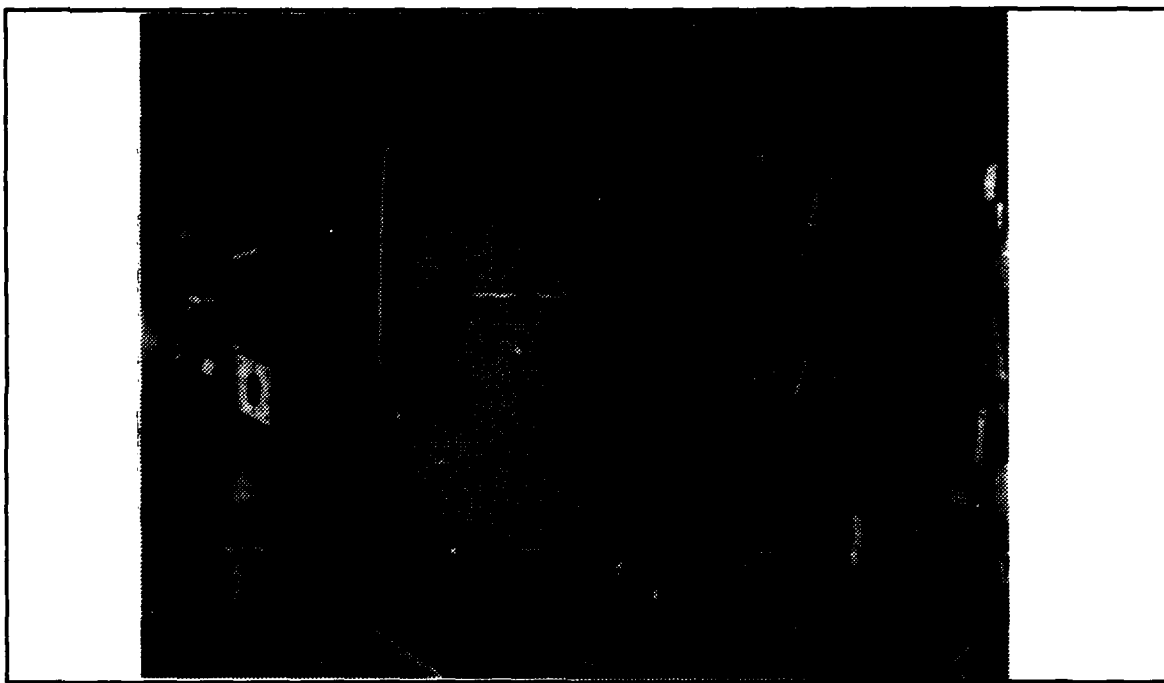
Figure 3.6. Solid Fuel Ramjet with Holocamera in Place

I. HOLOGRAM RECONSTRUCTION

A darkroom was used for developing the photgraphic plates and reconstructing the holograms. The reconstruction laser was krypton-ion. An optical microscope with 1X, 2X, 4X, and 10X oculars was attached to a mounting assembly for the lens-plate box. The laser and microscope were mounted on an optical table for vibration isolation. The entire assembly was adjustable to allow viewing of the 2.5 inch wide scene volume. The microscope also had provisions for mounting either 35 millimeter or video cameras.

IV. EXPERIMENTAL METHOD

The five different metallized fuels used during this investigation were provided by the Naval Weapons Center, and are listed in Table 1. Metal content was between 50% and 70% by weight.

TABLE 1. METALLIZED FUELS

Fuel #	Fuel Type
1	Boron Carbide/TEFLON DLX/Binder
2	Boron Carbide/Oxidizer/Binder
3	Silicon/Binder
4	Silicon/Oxidizer/Binder
5	Aluminum/Binder

The fuel slabs were cut to fit the combustion chamber, and were held in place with silicon adhesive. After the adhesive cured, measurements were taken to allow remote setting of step height, and the motor was reassembled (only one side was removed for fuel loading and cleaning). The windows were carefully cleaned , assembled, and roughly aligned. After mounting the holocamera, the Helium-Neon laser was first used to align the windows for a straight path. A sheet of paper was taped to a photgraphic plate which was mounted in the lens-plate box just as a normal plate would be. A pair of crosshairs were placed on the inlet window of the holocamera. With the lens-plate box installed, and the Helium-Neon laser on, the camera position was slightly adjusted to align the crosshair images in the scene and reference beams on the paper. As stated earlier, adjustments could be made in

three dimensions. Once set correctly, this arrangement needed very little attention. The ruby laser was allowed to warm up at reduced power during the alignment.

Pressure transducers and thermocouples, with their associated amplifiers, provided data needed to determine the mass flow rates of the inlet air, heater fuel, heater oxygen, and igniter fuel, as well as chamber pressure. All the above gases entered the system through sonic chokes. Given the area of the appropriate choke and the requisite constants, the computer program determined the mass flow rates based on conservation of mass for choked flow. A variety of chokes was available to ensure choked flow given a particular expected chamber pressure.

Normally, a reference wire was placed on the exit window of the motor to determine if a hologram existed, and if so to provide a scale for particle sizing. In later runs, a resolution target was used. The filter and shutter were installed in the lens-plate box, followed by the photographic plate. This assembly was placed in the holcamera, and the shutter connected to the laser firing circuit. With laser power turned up and all gas pressures set, the remainder of the run was carried out from the control room.

At this point in the run, the program in the HP-9836 prompted the input of four times: (1) a warmup time in which heater air alone passed through the motor to simulate flight conditions, (2) the ignition time for igniter firing, and the injection of additional ethylene, (3) the burn time for self sustained burning, and (4) the purge time, during which inert gas passed through the motor and inlet air was dumped overboard. Typical times were 8,2,4, and 4 seconds respectively. If a fuel proved particularly difficult to ignite, the warmup time and/or the ignition times could be increased slightly. After entering these times, the heater was manually ignited with the air dumping overboard. When the heater temperature reached

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approximately 600R, the laser charging circuit was switched on and the heater output was routed through the motor. At this point the computer assumed control based on the times above, and completed the run. The laser was fired manually approximately one to two seconds after ignition stopped, if the motor seemed to sustain. The data output was immediately available, and included air inlet temperature, chamber pressure, and mass flow rates for the air, heater fuel, heater oxygen, and ignition fuel; given every half second.

Normally, two good runs would exhaust the fuel. If the first run was successful (i.e., good ignition and sustained burning plus a hologram), the nozzle was changed for the second run to achieve a different chamber pressure. After two runs, the photographic plate was developed. The plate was replaced in the lens-plate box and mounted between the Krypton-ion laser and the microscope for reconstruction. The laser was shone through the back side of the plate at an angle similar to the one at which it was exposed by the reference beam. The holographic image then appeared in space at the same place as the subject, relative to the lens-plate box. The mount was such that the entire motor width, plus the reference target on the outside of the window could be reconstructed.

V. RESULTS AND DISCUSSION

A. METALLIZED FUEL COMBUSTION

A summary of all the runs performed during this investigation is included in Table 2. In general, the highly metallized fuels tested were quite particular about conditions required for ignition and self-sustained burning. One problem with the two-dimensional ramjet was loss of heat through the steel side walls which were not covered with fuel. To reduce this heat loss, black Plexiglas (polymethylmetacrylate) one fourth of an inch thick was glued to the side walls from the inlet aft, to about two inches upstream of the windows. Increasing the magnitude of any of the following variables should have increased the probability of sustained combustion, within limits: (1) inlet step height, (2) air mass flux (G), (3), chamber pressure, (4) inlet air temperature, (5) warmup time, and (6) ignition time.

TABLE 2. SUMMARY OF TEST RESULTS

TEST #	FUEL # (TABLE 1)	D_{th} in	G $\frac{lbm}{s-in^2}$	AIR	P_c IGN psia	RUN	f	T_i R	HOLOGRAM, IGNITION,SUSTAIN, COMMENTS
1	1	.75	.20	60	148	110	.0114	610	N,Y,N
2	1	.65	.20	73	119	76	.0114	1170	N,Y,N
3	1	.65	.20	73	125	76	.0107	1150	N,Y,N
4	1	.65	.20	73	140	78	.0111	1180	N,Y,N
5	1	.65	.20	72	145	76	.0093	1125	N,Y,N
6	1	.65	.20	72	120	74	.0092	1080	N,Y,N
7	1	.65	.20	71	109	72	.0093	1066	N,Y,N
8	2	1.10	.35	45	55	46	.0094	1295	N,N,N
9	2	1.10	.35	45	81	47	.0092	1310	N,Y,N
10	2	1.35	.50	44	46	44	.0086	1050	N,N,N

TEST #	FUEL # (TABLE 1)	D_{th} in	G lbm s-in^2	P_c AIR psia	P_c IGN psia	P_c RUN psia	f	T_i R	HOLOGRAM, IGNITION,SUSTAIN, COMMENTS
11	2	1.35	.50	42	44	42	.0090	1090	N,N,N
12	2	1.35	.50	42	75	44	.0090	1100	N,Y,N
13	3	1.35	.50	42	45	43	.0090	1085	N,N,N
14	3	1.35	.50	42	43	42	.0095	1125	N,N,N
15	3	1.35	.50	15	15	62	.0095	1000	N,N,N,Heater failed
16	3	1.10	.50	64	134	62	.0094	1135	Y,Y,N
17	3	1.10	.50	65	140	100	.0095	1155	Y,Y,Almost
18	HTPB/2	1.10	.50	65	66	66	.0087	1060	N,N,N
19	HTPB/2	.85	.35	82	163	155	.0092	1325	Y,Y,Y
20	HTPB/2	.85	.35	82	170	153	.0099	1385	Y,Y,Y
21	HTPB/3	.85	.35	81	161	147	.0080	1310	Y,Y,Y,Collimated
22	HTPB/3	.85	.35	79	156	139	.------	1315	Y,Y,Y,Diffuse
23	HTPB/2	.85	.35	76	152	139	.0082	1190	Y,Y,Y,Collimated
24	HTPB/2	.85	.35	78	151	145	.0093	1320	Y,Y,Y,Diffuse
25	HTPB/2	.85	.35	78	154	117	.0081	1195	Y,Y,Y
26	HTPB/2	1.10	.35	45	55	45	.0080	1190	N,N,N
27	HTPB/2	.95	.35	62	124	96	.0081	1210	N,Y,Y,No laser fire
28	HTPB/2	.95	.35	60	125	61	.0079	1175	Y,Y,N
29	HTPB/2	.95	.35	60	128	93	.0080	1190	Y,Y,Y
30	HTPB/2	.95	.35	60	125	108	.0079	1173	Y,Y,Y
31	HTPB/4	.85	.35	75	151	127	.0081	1215	Y,Y,Y
32	HTPB/4	.95	.35	60	66	61	.0081	1215	N,N,N
33	HTPB/4	.95	.35	61	120	111	.0081	1230	Y,Y,Y
34	HTPB/5	.85	.35	77	157	130	.0080	1195	Y,Y,Y
35	HTPB/5	.95	.35	63	123	93	.0079	1175	Y,Y,Y

Notes: D_{th} = nozzle throat diameter

$$G = \text{air mass flux} = \frac{\text{air mass flow rate}}{\text{fuel port area}}$$

P_c = combustion chamber pressure

$$f = \text{fuel-air ratio} = \frac{\text{heater fuel mass flow rate}}{\text{air mass flow rate}}$$

T_i = inlet air temperature

In instances where consecutive runs appear to be identical, the step height or times were normally changed. Some difficulty with the heater fuel pressure transducer resulted in an inability to affect temperature in a few cases. The target temperature was 1200R. Initially, chamber pressure was increased by using a smaller nozzle and increasing ignition time. The boron carbide would normally ignite, but not sustain under these conditions. Next, air mass flux was increased, and chamber pressure was decreased. The boron carbide and silicon fuels normally would not even ignite with these conditions. In test sixteen, the nozzle size was decreased to 1.10 inches, with $G = 0.50$. The fuel ignited well in this and the subsequent test, but failed to sustain. At this point, the decision was made to replace the top metallized fuel slab with hydroxy-terminated polybutadiene (HTPB), a hydrocarbon fuel known to burn easily, as well as very hot. It was hoped that heat release from the combustion of the HTPB would aid in the burning of the bottom slab. The first attempt with a boron carbide fuel failed. It seemed that the very high air mass flux caused the blowoff limits of the fuel to be exceeded, since the fuel would not even ignite as it had previously. The air mass flux was reduced to 0.35, and the nozzle size was decreased to give an air-only chamber pressure of about 80 psia. Under these conditions, every fuel ignited and sustained with no difficulty. Ignition times of as little as half of a second were noted. Chamber pressure during the runs was about 140 psia.

In an attempt to compare data at different chamber pressures, the nozzle size was increased to 1.10 inches, again (Test 26). The boron carbide did not ignite. The nozzle size was reduced to 0.95 inches yielding air-only chamber pressures of about 60 psia. Reasonable success was had at these conditions, with at least one good run for each fuel. Chamber pressures during the runs were around 100 psia.

It was interesting to note the amount of accretion of solid matter around the nozzle and in the aft mixing zone. The boron carbide fuel produced a thin film of powdery solid. The silicon produced relatively large amounts of brown, coarse material imbedded with glassy particles. The layer around the nozzle was approxi.nately one quarter inch thick. The aluminum fuel produced copious amounts of gray, coarse solid with metallic particles imbedded.

B. HOLOGRAPHY

After initial attempts to align the laser, holocamera, and motor, several modifications were applied. As mentioned previously, two-dimensional translators were added to the camera mount. As constructed, the scene volume would have been illuminated with the outside edge of the laser beam. The motor was raised one half inch to make the center of the laser beam coincident with the fuel surface.While attempting fine adjustment of the mirrors in the camera, it was discovered that the mount for the lens-plate box was displaced about six one hundredths of an inch from exact alignment. The camera was disassembled and milled in order to center the box. After the modifications, alignment of the system was relatively easy.

A standard Air Force resolution target was used for initial system testing. The objects in this target were rectangular. Figure 5.1 shows a photograph of a hologram of this target. With no windows in the motor, resolution was approximately 11 microns, very close to that reported by Easterling [Ref. 4:p. 37]. Testing with the same target, and the windows in place, yielded approximately fifteen micron resolution. Later reference holograms were taken with a particle resolution target. These round objects were much more difficult to see, and resolution was about 24 microns with the silica windows in place. A photograph of

a hologram of this target is shown in Figure 5.2. The silica windows were added in an attempt to improve resolution. They did not apparently improve resolution, but were much easier to clean than the Plexiglas. They also did not melt or char like the Plexiglas, and were therefore usable many times. To determine the effects of the smoke in the combustion chamber on the holograms, the particle resolution target was placed on the window outside the motor during several runs. The resolution in these holograms was basically identical to the resolution of the reference holograms. It was obvious in looking at the holograms with the naked eye that the intensity of the scene beam reaching the plate varied from run ro run. In some cases, it was invisible within the larger reference beam, but most often it was of considerably greater intensity. Resolution did not seem to change appreciably in the two cases.

Only two collimated light holograms were attempted during the investigation. In the first, the scene beam, unattenuated except by combustor smoke, spattered the photographic emulsion on the plate. In the second, a neutral density filter was placed in the scene beam and the hologram was good. The problem with this hologram was the tremendous schlieren effect from the thermal gradients in the combustor. The reference wire which was outside the combustor was clearly imaged, but the scene volume was not usable.

The remainder of the holograms were taken with a piece of diffuse glass in the scene beam. The idea was to create a very large number of tiny laser sources instead of one large collimated beam. The effect was a smearing of the very much smaller schlieren patterns into a background speckle. This speckle caused the resolution problems. When reconstructing holograms with the particle resolution target in place outside the motor, there were areas of speckle in the field of view

which were larger than the smallest particle visible on the target. In other words, even when the resolution based on the target was known, there was still considerable uncertainty about resolution throughout the image. It was interesting to note that there was very little material of appreciable size (say, greater than 25-30 microns) in any of the holograms. Figure 5.3 shows a hologram with a very large flake of material about to depart the fuel surface on the left. Figure 5.4 shows a hologram with several large particles in the flow above the fuel surface.
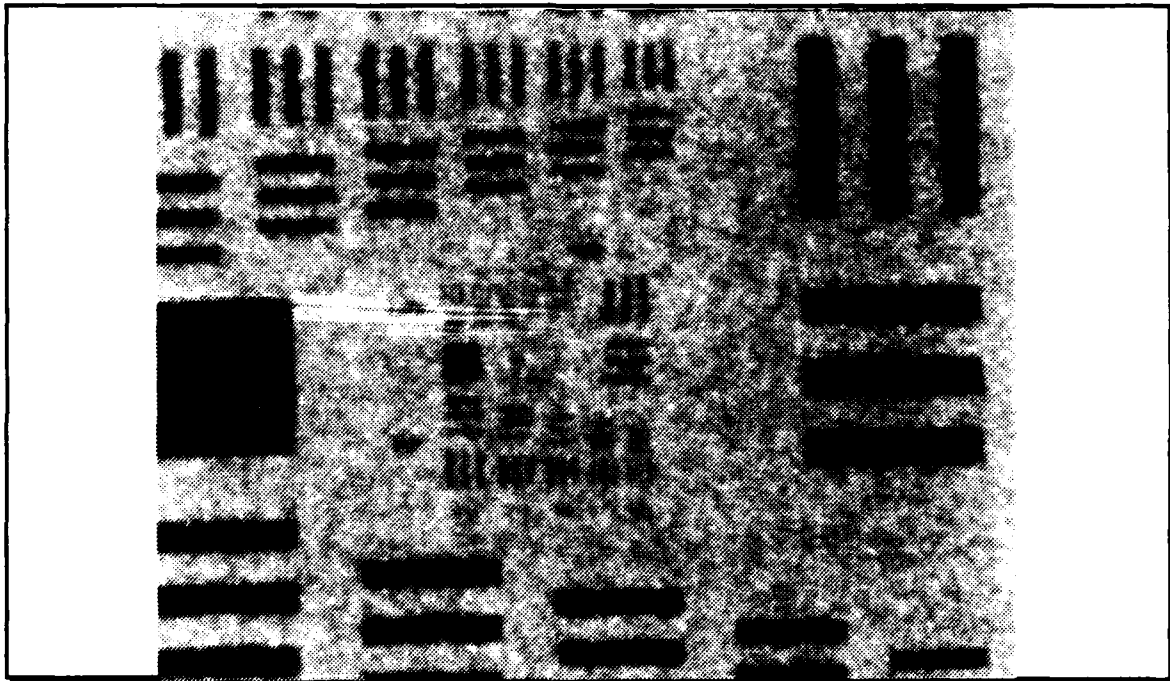

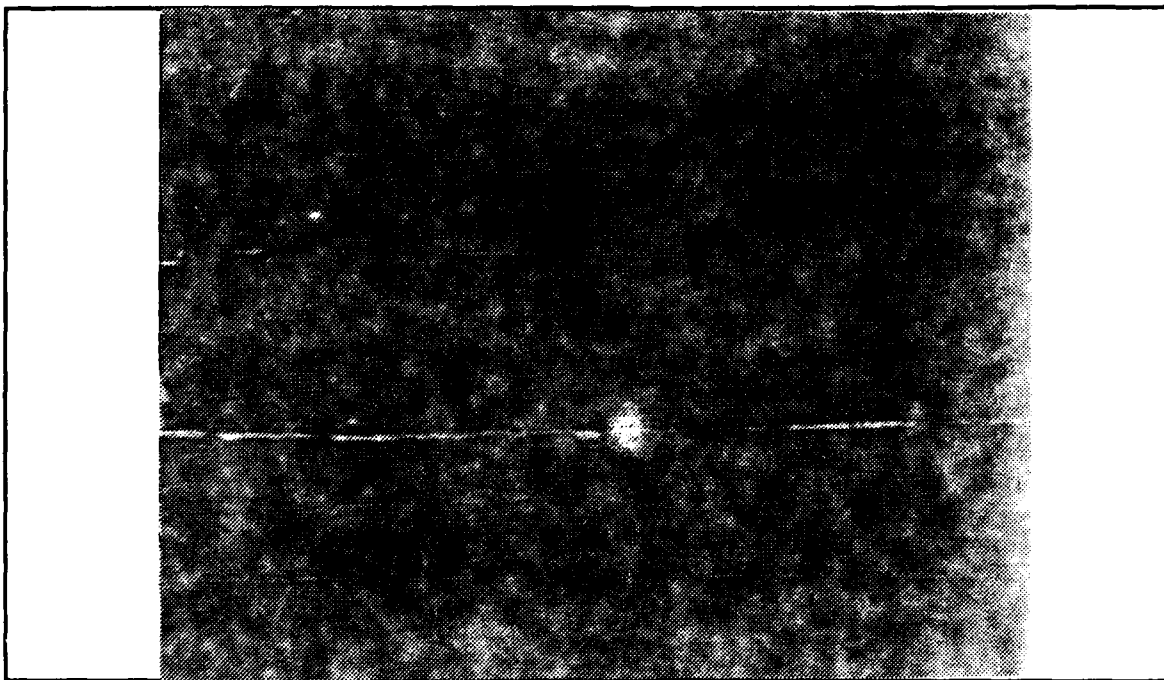**Figure 5.1. Hologram of Air Force Resolution Target**

Figure 5.2. Hologram of Particle Resolution Target

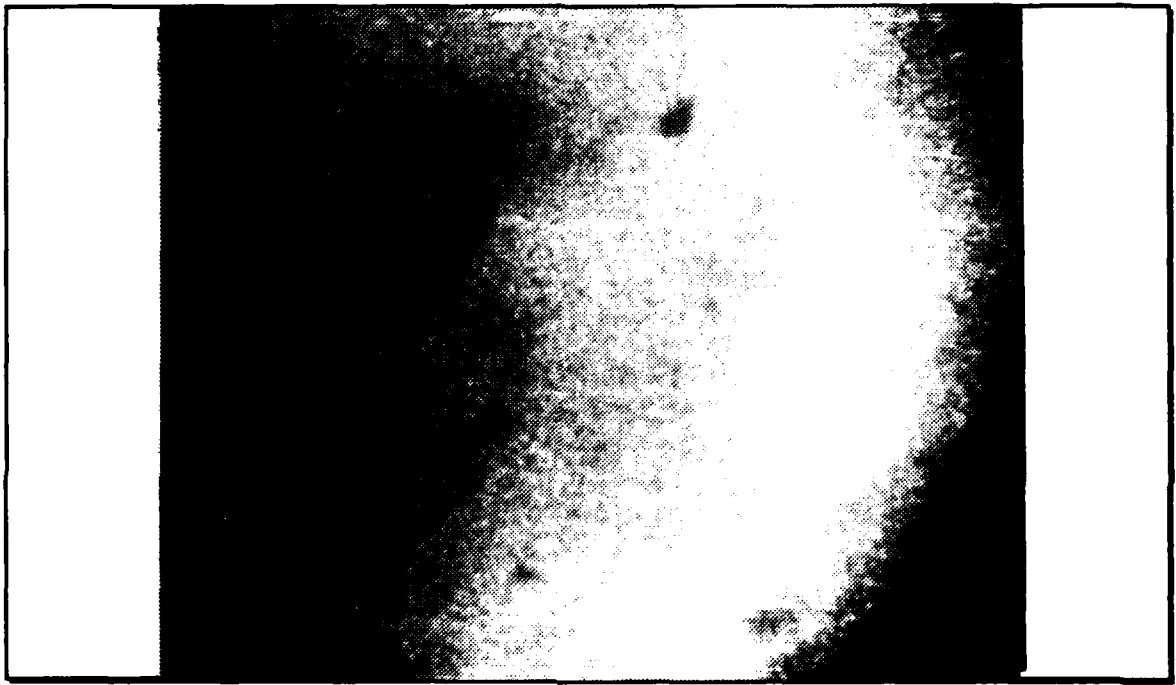**Figure 5.3. Hologram of Large Surface Flake**

Figure 5.4. Hologram Showing Several Large Particles

VI. CONCLUSIONS AND RECOMMENDATIONS

The holographic technique used in this investigation is certainly capable of producing quality holograms of the solid fuel ramjet combustor, even in the presence of copious amounts of smoke generated by the metallized fuels. However, the holograms taken did not indicate much material larger than the resolution limits of the holograms. Most of the material that was obvious in the holograms was very ι ιge (greater than 200 microns) and irregularly shaped, and could probably be assumed to be flakes of binder. Differences in the intensity of the scene beam from one run to another indicate that the beam is attenuated differently from run to run. There was not an appreciable difference in the resolution from one hologram to the next. If the ratio of scene beam intensity to reference beam intensity is considered critical, it would be very difficult to predict the amount of attenuation required based on the amount of smoke in the combustor, as that amount can change considerably even during a run.

The metallized fuels used in this investigation proved very difficult to sustain under conditions providing easy combustion for most hydrocarbon fuels. One of the most critical parameters was the chamber pressure, which had very narrow limits, even with the HTPB on the top half of the chamber. When within the limits, though, all the fuels ignited very quickly and sustained easily. A better solution to the side wall heat loss problem in the two-dimensional motor could possibly expand the envelope of operation for these fuels.

For holography to be a useful diagnostic tool for solid fuel ramjet combustion of metallized fuels, resolution must be improved. The vast majority of the particles seem to be smaller than the current resolution limits. Light scattering methods may

be the answer in terms of resolution. However, ensemble systems average the scattering for the entire scene volume. Large flakes or window fowling would be included in this average. Single particle counters may not be adequate due to the high number of particles and the high flow velocities.

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